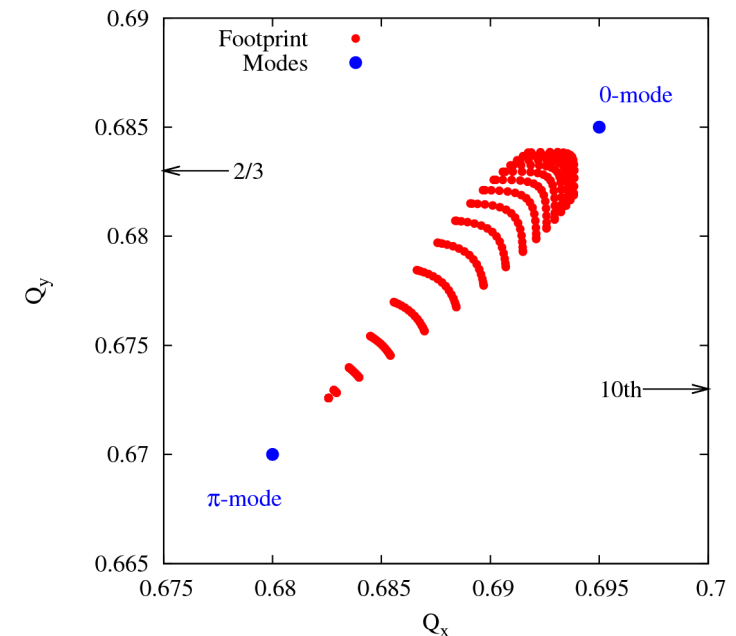# Beam-Beam Studies for Polarized Protons

S. White, W. Fischer, Y. Luo

2011 Beam Parameters

- Beam parameters in 2011 (measured intensity + design tunes, emittance):

|	
Intensity [p/bunch]	1.65e11
Tunes [x,y]	0.695 / 0.685
Emittance [π.mm.mrad]	20
ΔQ [2IP]	0.012

- Current working point between 10th and 2/3rd resonances

- Coherent modes extend to $Y.\xi$ (Yokoya factor $Y\sim1.23$)

- Further increasing the bunch intensity will bring us to the "beam-beam limit"

How can we Gain Space?

- **Move to the integer tune:**

  - See M. Bai's talk – this workshop

- **Head-on beam-beam compensation (electron lens):**

  - Reduces the incoherent tune spread
  - Coherent modes (almost) not affected

- **Coherent beam-beam studies:**

  - Do we understand the current picture?
  - How sensitive the π-mode is to the 2/3rd resonance? How much can we gain?
  - **Suppression:** tune split – synchro-betatron effects?

- **Increase the luminosity at the beam-beam limit**

 - Can we operate RHIC with a crossing angle?

Coherent Beam-Beam Modes at RHIC

- Coherent beam-beam modes routinely observed during regular operation using beam transfer function measurements:
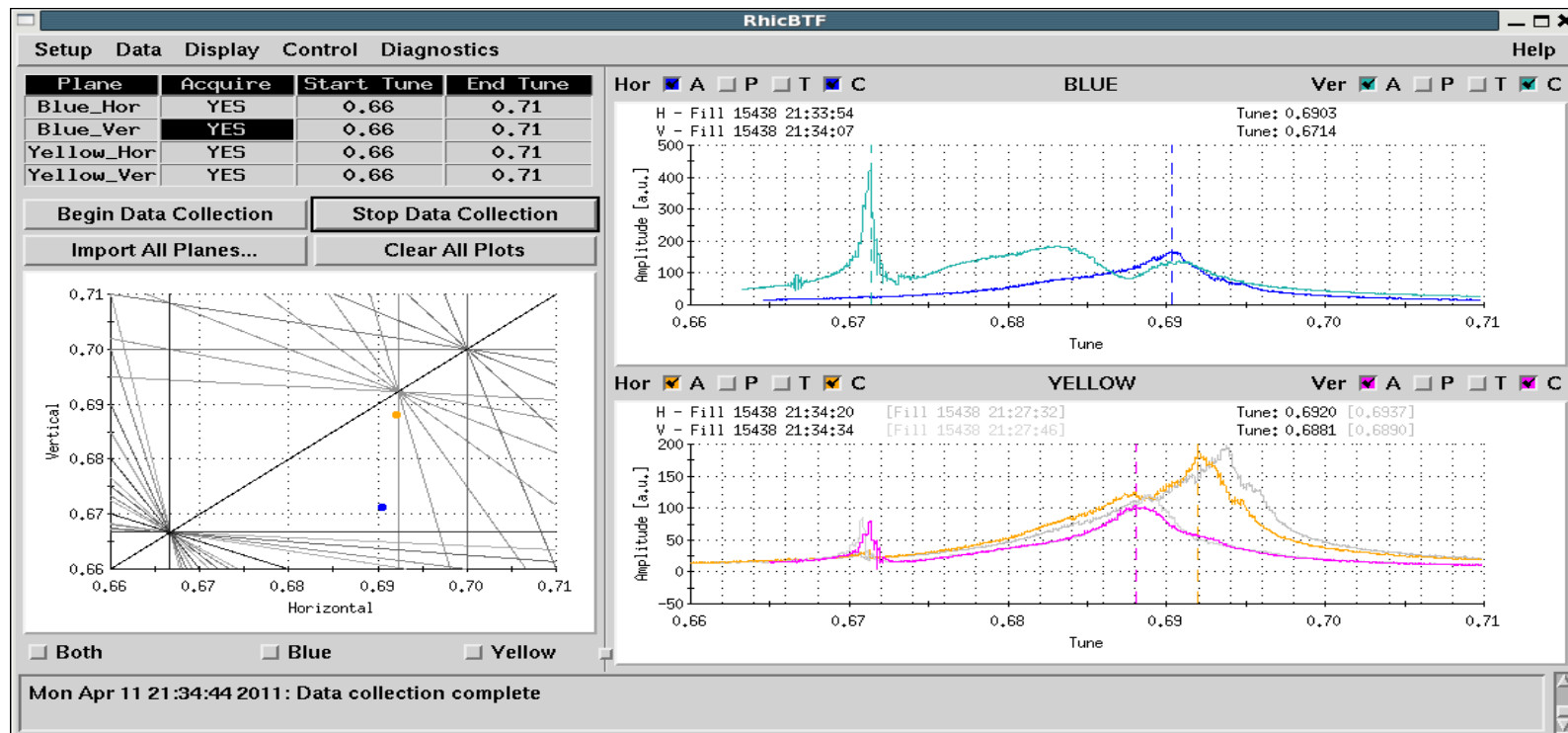
- **Vertical plane:** clean 0 and π-modes observed

- **Horizontal plane:** π-mode not observed – What is the source of the damping?

  Could this be used in the vertical plane as well? - **Not understood yet**

10 Hz Triplet Vibrations
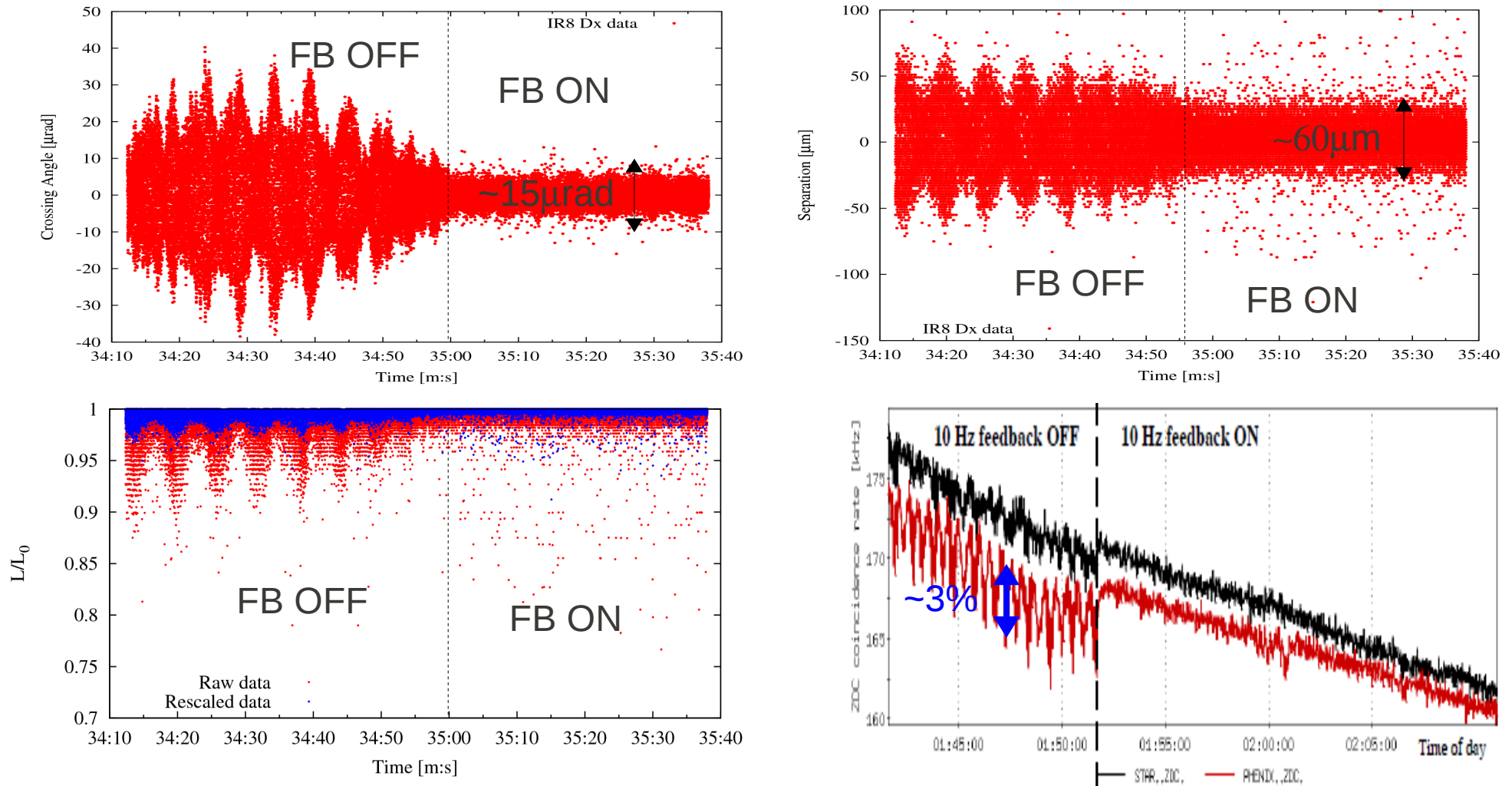
- FB system clearly brings down modulations
- Still some non-negligible leftovers → DX data very noisy – **is this real?**
- **Calculated effect on luminosity larger than what is seen in the data**
- **Reduce the separation by a factor 2 to match the data – still ~0.3 σ peak-to-peak**

Simulations

- Strong-strong simulation with orbit fluctuations (1 IP only) . Assumed 10Hz sine fluctuations – probably not fully realistic – additional FB noise?
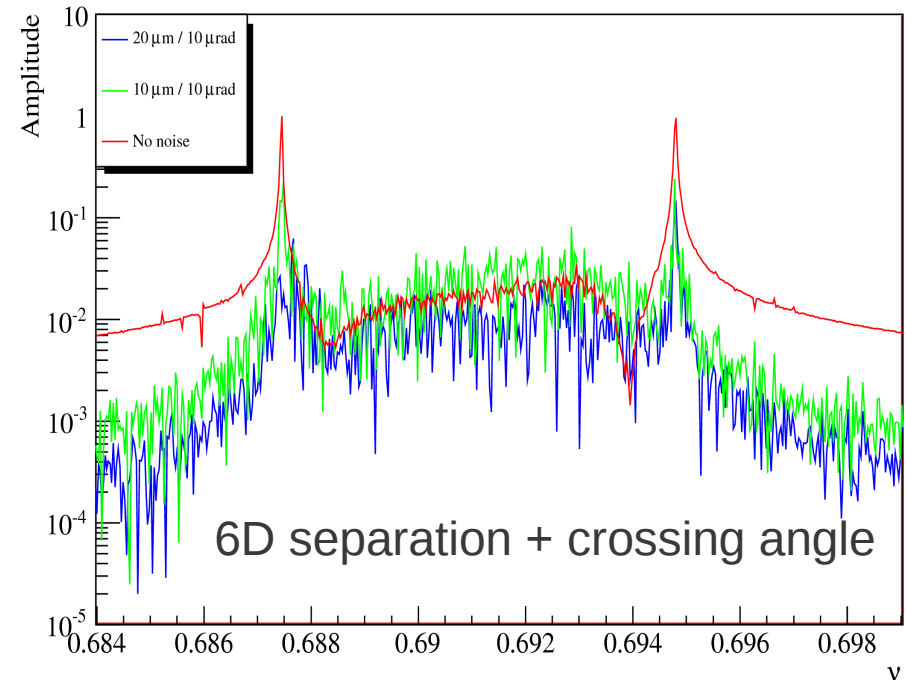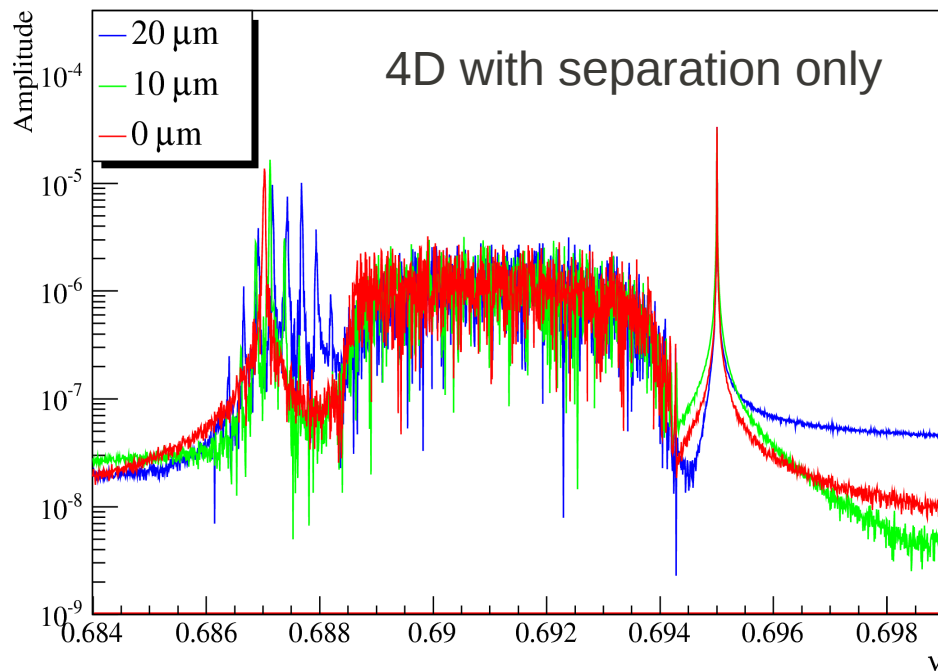

- **4D:** Separation only → π-mode modulated by 10Hz

- **6D:** lower resolution (less turns) → π-mode damped by the noise

- **Both cases show clear effect on the π-mode**

Experiment Proposal

- **Goal:** understand the effects of the leftovers from the FB systems on the coherent beam-beam modes and lifetime

- **Experimental setup:** use the old feedback system magnets (rotated) to modulate the orbit in the vertical plane – **needs to be tested first**

- **Beam conditions:** as close as possible the physics conditions at beginning of stores – 3x3 filling pattern

- **Experiment:** Scan amplitude (frequency?) and observe the effect on lifetime and coherent modes (BTF measurements) – **estimated time ~2-3h**
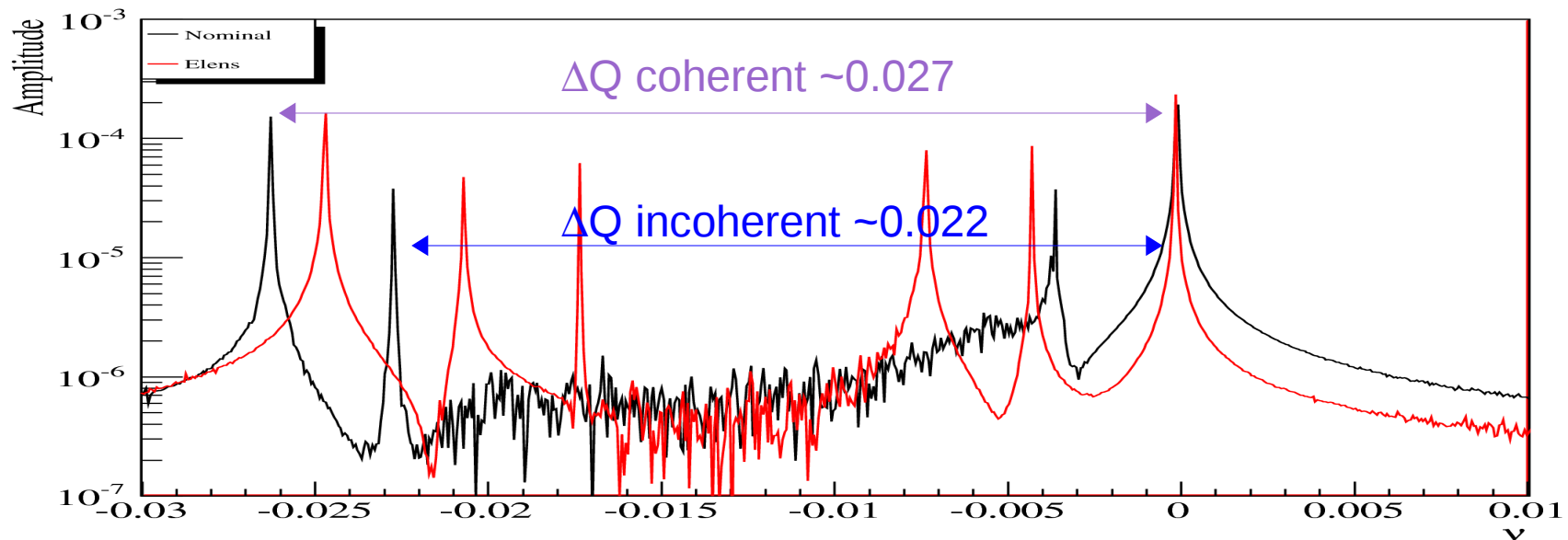
	y [m]	y' [μrad]
IP6	7.01e-05	71
IP8	-5.14e-06	129
IP2	9.44e-05	-51

Orbit distortion (MADX) at the IPs for maximum kick in q3o6 (large β)
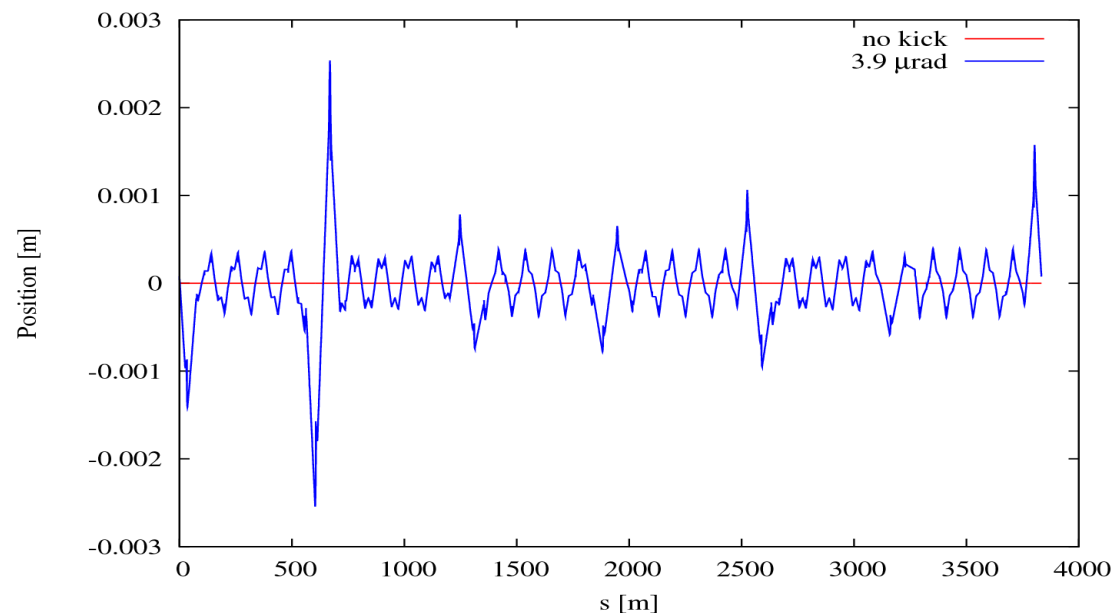
Coherent Modes with HD Compensation

- Take the simplest situation: 3x3 colliding in IP6 and IP8 – 3e11 p/bunch would give a HD tune shift ~0.022 (coherent ~ 0.027)

- Case w/o electron lens - additional modes w.r.t. the data:

  - Position of the "inner" modes depends on the phase advance IP-to-IP → here lattice largely different from "nominal"

  - Very close to the incoherent continuum → additional non-linearities (chromaticity, multipolar field components) could damp them

- **Coherent modes almost no affected by the elens → loss of landau damping? What about betatron resonances (2/3rd)?**

Coherent Instability Observed at the LHC

- Coherent beam-beam modes observation at the LHC: *X. Buffat et al., "Observation of Coherent Beam-Beam Effects in the LHC", IPAC11*
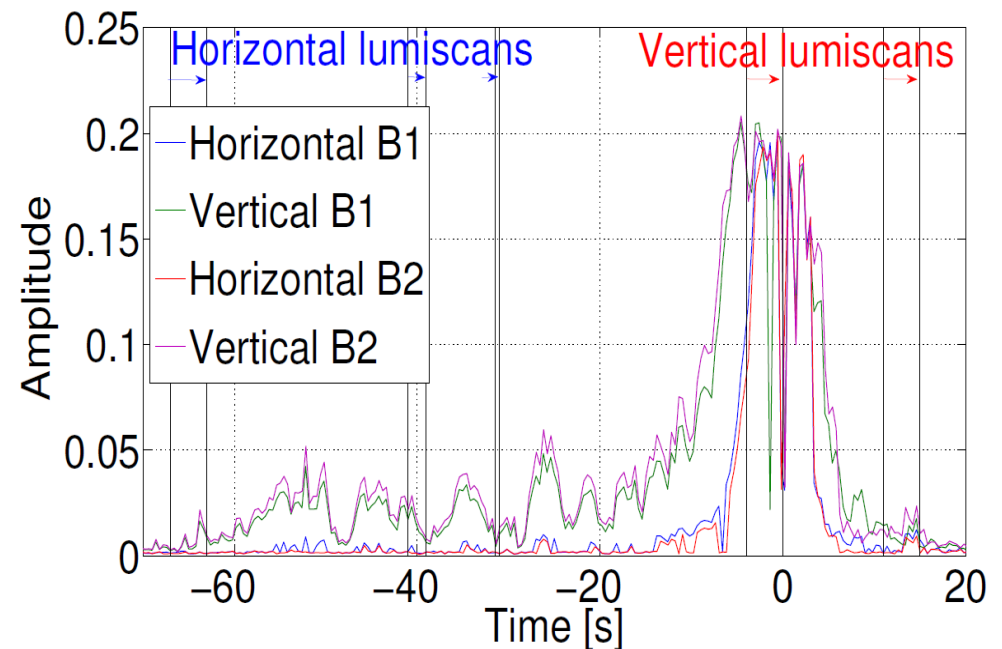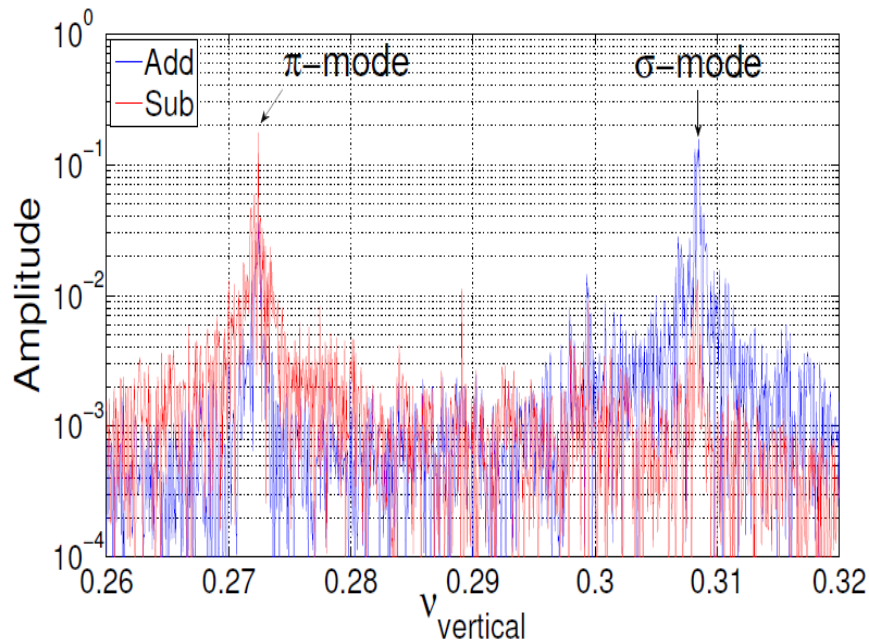
- **Coherent modes observed without external excitation**: not naturally damped

- **Coherent instability was observed** – impedance under investigation

- In regular physics conditions the transverse damper is always on. Coherent modes or instabilities not observed

- **Coherent modes can become unstable if not damped → issue for the elens?**

Coherent Modes Suppression

- Even if the 10 Hz noise is the source for the damping in the horizontal plane this should NOT be used as a damping tool → emittance/lifetime

- A simple solution to suppress the coherent mode is to use a tune split
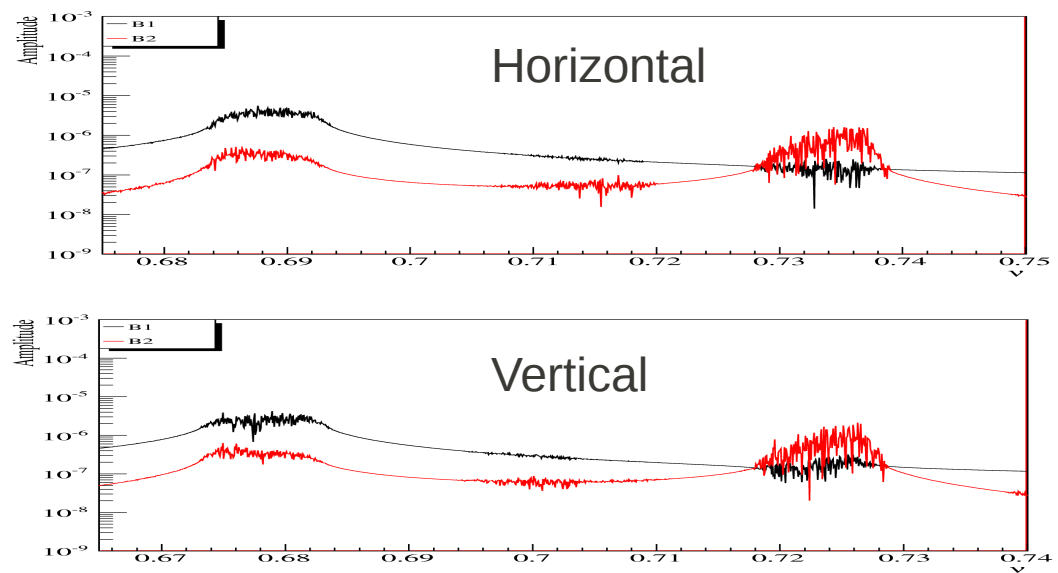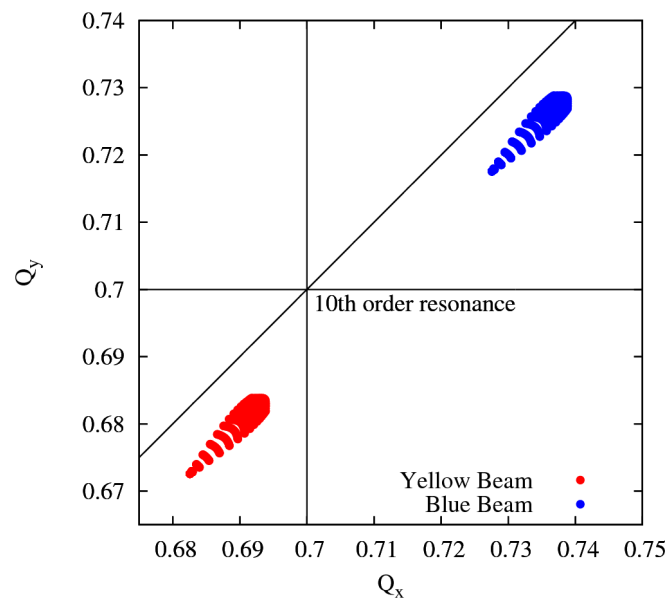
- Stay as far as possible to the 10th order resonance

- Lifetime close to 0.75 should be ok – LHC: 0.31 / 0.32

- Provides sufficient tune split to fully suppress the coherent modes

Experiment Proposal

- **Goal:** Measure the impact of the coherent modes on lifetime, $2/3^{rd}$ resonance stop-band, available space in the tune diagram. Comparison with and without coherent modes.

- **Beam conditions:**
  - 6x6 with only 3x3 bunches colliding at the time (filling pattern)
  - maximum head-on tune shift desirable (high bunch intensity)
  - Bunches should be as equal as possible for comparison

- **Experiment – one store:**
  - Collide the first three bunches – tune scan, measure 2/3 stop band – only the colliding bunches should suffer (HD tune shift)
  - Separate beams – move one beam to ~0.75
  - Rotate longitudinally, collide the remaining 3 "fresh" bunches and repeat first point

- **Estimated time:** 2h maximum

Operation at the Beam-Beam Limit

- When operating at the beam-beam limit we can use the properties of the crossing angle to further increase the luminosity:
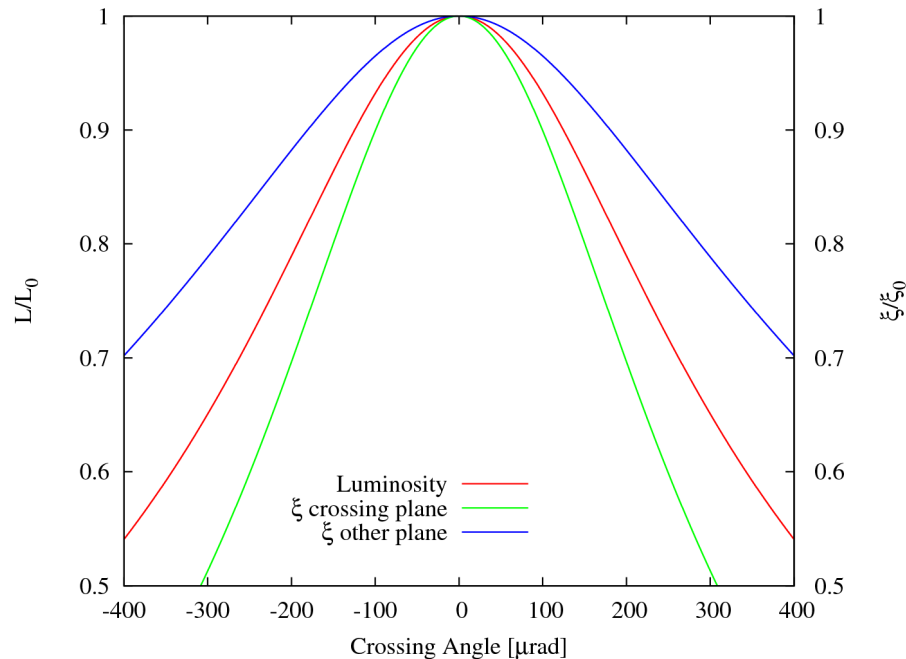
Luminosity and Beam-Beam parameters as function of the crossing angle

$$\xi_x = \frac{N r_0}{2\pi \sigma_x F(\phi)(\sigma_y + \sigma_x F(\phi))}$$

$$\xi_y = \frac{N r_0}{2\pi \sigma_x (\sigma_y F(\phi) + \sigma_x)}$$
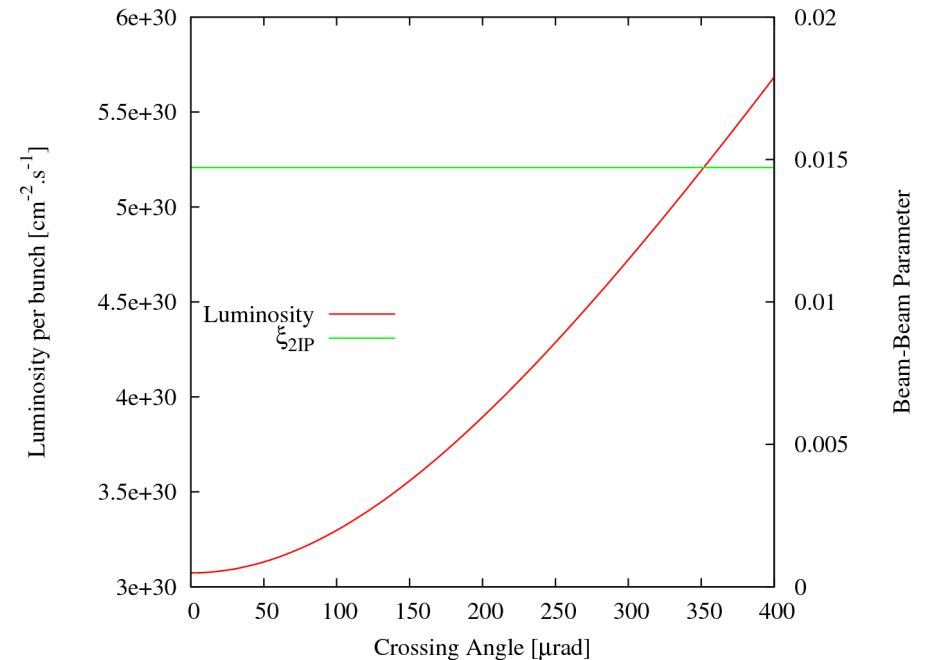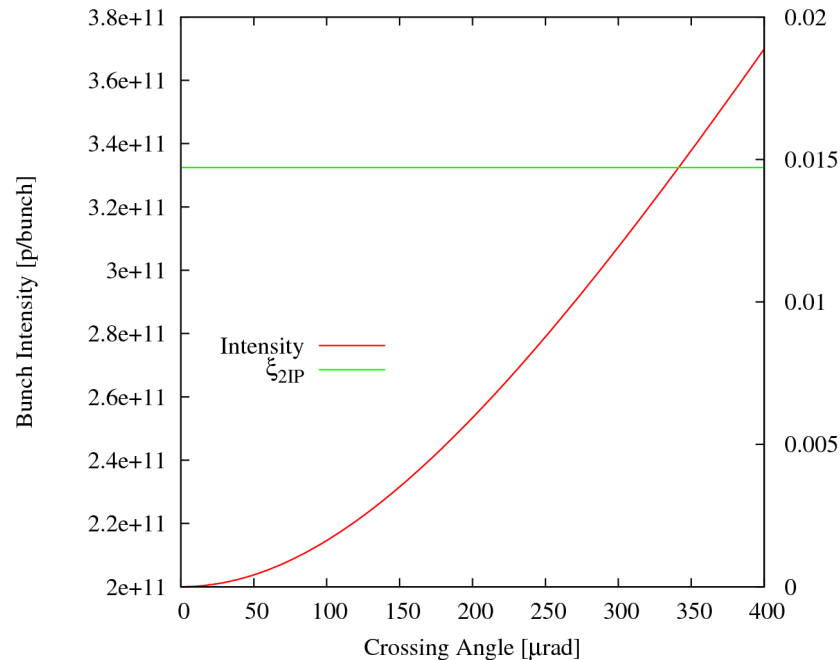
$$L(\phi) = \frac{L_0}{F(\phi)} \propto N^2$$

Use 2 IPs and alternate crossing angle. For round beams:

$$\xi_x + \xi_y \propto \frac{N}{F(\phi)}$$

Keep ξ_{tot} constant using N => L increases linearly with N

Possible Gain for RHIC

- Assume the beam-beam limit is around 2.0e11 p/bunch
- This technique requires high bunch intensity – new source
- It should be possible to accommodate 200 µrad angle with regular orbit correctors
  → about 20% gain – much larger with DX and D0
- Also allows for leveling
- **Prerequisites:** what intensity can we reach? what are the maximum tune shift and crossing angle?
  => Last two points can be checked without the new source
  => Could be a good alternative until the elens is operational

Synchro-Betatron Effects

- Operating with a crossing angle will excite synchro-betatron resonances through the beam-beam force – damping of the π-mode depends on Q_s / ξ
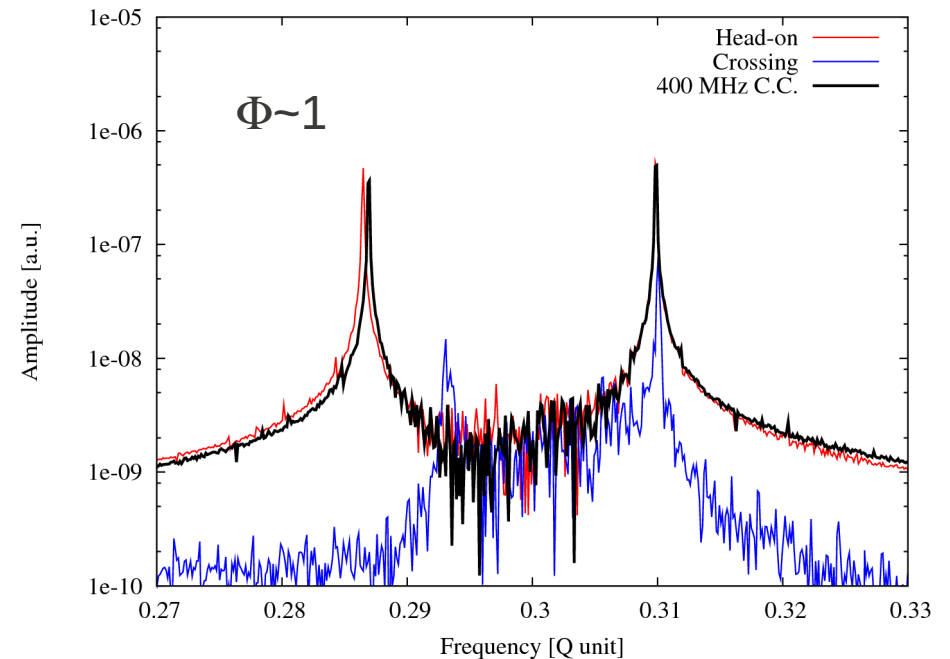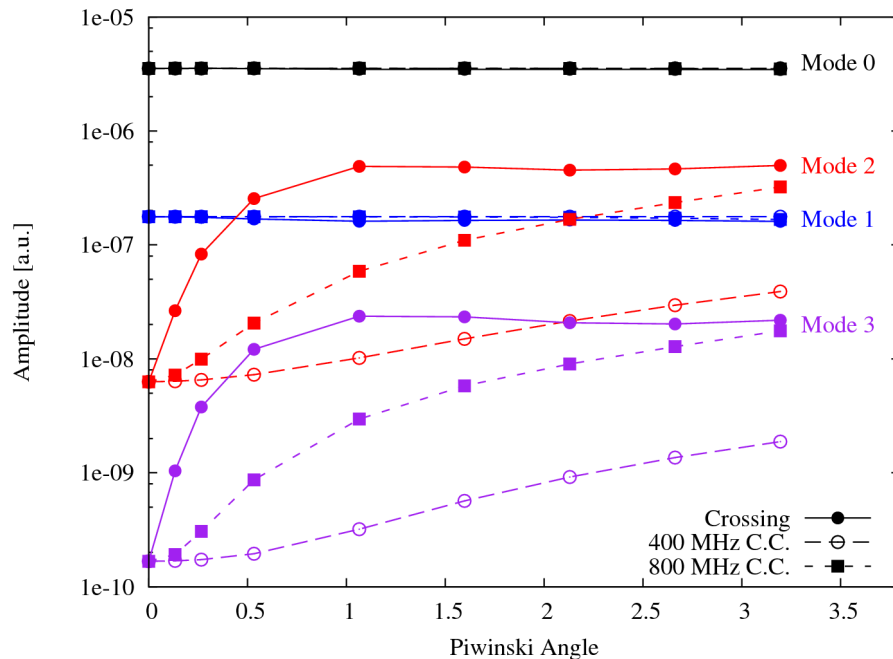
- Simulations done for HL-LHC: $Q_s \sim 0.002$, at RHIC $Q_s \sim 0.0005$

- Taking RHIC parameters and assuming 200 µrad angle $\Phi \sim 0.9$ and $\xi \sim 0.01$. To be compared with $\Phi \sim 1$ and $\xi \sim 0.015$ in the simulations

- We are about a factor 3 off → **colliding only one IP and increased Q_s should bring us in the damping regime – never observed experimentally (to my knowledge)**

Experiments Proposal

- **Goals:**

  - Measure the residual crossing angle (angle scans)

  - Assess the maximum achievable tune shift and crossing angle

  - Synchro-betatron effects with large Piwinski angle (academic)

- **Experiment – 2 stores:**

  - **1st store:** physics conditions (fewer bunches): measure residual crossing angle and determine maximum crossing angle

  - **2nd store:** inject high intensity bunches (3x3) with crossing angle in – increase tune shift by decreasing the crossing angle

  - **Alternative:** fill the machine with bunches of different intensity / un-squeezed beams (more aperture)

  - For each store measure lifetime, emittance, coherent modes vs crossing angle

- **Estimate time:** 2x2-3h – two APEX sessions - 2nd store parameters will depend on the results of the first experiment

HL-LHC Studies

- Most efficient way for BNL to contribute to HL-LHC is through beam experiments which are also interesting for RHIC

	HL-LHC Parameters
N [p/bunch]	**2.0e11**
ε_N [μm]	**2.5**
Q_x / Q_y / Q_s	0.31 / 0.32 / 0.002
β^* [m]	**0.15**
σ_s [m]	0.075
dp/p	1.129e-4
θ [μrad]	**475 (~10σ)**
N_{LR}	**18-24**
L_{peak} [cm^{-2}s^{-1}]	7.4e34 (2.0e35 w. CC)

- **Target is to reach 2.0e35 virtual luminosity leveled to 5e34**

- Can be achieved with **crab cavities and leveling with crossing angle**

- Recent studies indicate that the **crossing angle may have to be increased to 600 μrad**

- **Relevant beam-beam studies:**
  - Long-range interactions
  - Crab cavity noise
  - Synchro-betatron effects with large Piwinski parameter

- **Some useful studies can be done at RHIC**

What can we do at RHIC?

- **Beam-beam and noise was identified as a possible issue for operation with crab cavities – also relevant at RHIC for the electron lens:**

  - 10Hz noise study already proposed – what would be really interesting for HL-LHC is "white noise"

  - How easy would it be to inject "white noise" into the RHIC beam? Damper?

- **Large Piwinski angle is also of some interest:**

  - With nominal parameters we can only reach $\Phi \sim 1$ with significantly smaller synchrotron tune

  - Is it possible to use DX and D0 magnets? Can we increase the synchrotron tune? Up to which value?

- **Coherent beam-beam studies also triggered interest**

- Except for LR interaction the problematic for HL-LHC is similar to RHIC – and the proposed studies could be compatible with existing RHIC proposals. **CERN expressed interest in conducting joint experiments if time is allocated**

Summary

- **3 experiments proposed for an estimated time of about 10h:**

  - 10 Hz noise (2-3h)

  - Tune scan / tune split – coherent modes suppression (2h)

  - Crossing angle measurements / maximum head-on tune shift / SB effects (2x2-3h)

  - Some of these experiments can be combined to optimize beam time

- **The main goal is to understand the current limitations and identify possible issues for operation with electron lens**

- **CERN expressed interest in joint experiments:**

- Most of the proposed studies would be compatible which current APEX proposals

- Priority seems to be the study of beam-beam & noise ("white noise" preferably)